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Leadign Community Risk Reduction

Assessment of Tsunami Hazard and Related Mitigation Plans in Bellingham, Washington

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CERTIFICATION STATEMENT

I hereby certify that this paper constitutes my own product, that where the language of others is set forth, quotation marks so indicate, and that appropriate credit is given where I have used the language, ideas, expressions, or writings of another.

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Abstract

As officials were unsure of the vulnerability of the City of Bellingham to the threat of tsunamis, this purpose of this research was to assess that vulnerability and to identify best practices for mitigation. The descriptive method was used to gauge the probability of a tsunami reaching Bellingham, discover the likely extent of inundation, identify elements at risk, catalog mitigation alternatives, and to assess the adequacy of local plans to address the threat of tsunamis.

Procedures included use of a risk assessment tool. Results suggested that areas within Bellingham's inundation zone have a low vulnerability to the effects of tsunamis, and that there are gaps in local plans. Recommendations include vitalizing local emergency management planning, and implementing information tools.

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Introduction

Tsunami (soo-NAH-mee). Combination of the Japanese words for ‘harbor’ (‘tsu’), and ‘wave’ (‘nami’). Term used by Japanese fisherman to describe the wave caused devastation seen upon returning to port although they didn’t detect any unusual waves while out at sea (Tibballs, 2005).

An earthquake along the Cascadia fault is thought to have the potential to create a tsunami that could reach the City of Bellingham, Washington. The tsunami could come from either movement of the seafloor off the coast, or from locally occurring landslides. Scientific research, some of which is based on the 2004 Indian Ocean tsunami, differs on the potential magnitude of a Cascadia tsunami. The City of Bellingham Fire Department is unsure of the city’s vulnerability to tsunamis, and of the best approaches to mitigate their effects.

This research will identify the vulnerability of the City of Bellingham to tsunamis and identify best practices to enable the city to reduce loss of life and property from such an event over the long term. The following questions will be addressed:

1. What is the probability of a tsunami reaching the City of Bellingham?
2. What is the likely extent, if any, of tsunami inundation into Bellingham?
3. What elements, if any, of Bellingham are vulnerable to the threat of tsunamis?
4. What measures are available to mitigate the effects of tsunamis?
5. How should the plans, if any, to mitigate the effects of a tsunami reaching Bellingham be improved?

Background and Significance

The City of Bellingham lies in the northwest interior region of Washington State, approximately 50 miles south of Vancouver, British Columbia. Bellingham serves as the regional retail, transportation, medical, and educational hub for northwestern Washington. The first stop for southbound Amtrak trains from Canada, Bellingham hosts the southern terminus of the Alaska Ferry, and is home to Western Washington University. 71,289 people live in the 26 square miles of the city (United States Census Bureau, 2006).

Bellingham is situated on Bellingham Bay, which opens to the San Juan Islands and the Strait of Georgia. Although originally settled on the bluffs surrounding the bay, the waterfront land area has been greatly expanded from its original size due to over 100 years of earth filling activity. The composition of the waterfront area is transitioning from its past as a home for resource-based industries including fishing, timber and pulp, shipping and boatbuilding, to a diverse future use. Dominating the waterfront is the Port of Bellingham's Squalicum Harbor. The harbor is the second largest marina in Washington State, and hosts the largest cold storage facility on the west coast of the U.S. Currently, the city and the Port of Bellingham are collaborating to redevelop 137 acres along the central waterfront. The vision is to create a new neighborhood with homes, shops, offices, light industry, parks and a new marina (New Whatcom Master Plan, 2006).

The Bellingham Fire Department provides a full range of emergency medical and fire services within the City of Bellingham, as well as advanced life support services and the bulk of the ambulance transport service to the additional 108,878 citizens of Whatcom County (United States Census Bureau, 2006). Although the fire department is considered the lead department for emergency management activities within the city, comprehensive emergency management

services are obtained by contract through the Whatcom County Sheriff Office's Division of Emergency Management.

Based on the simple fact that Bellingham is a coastal community located proximate to the earthquake prone Cascadia subduction zone, understanding the threat posed by tsunamis, and identifying steps to mitigate the possible effects, is of keen interest to the fire department. Additionally, Bellingham residents and city officials have a heightened awareness of the effects of a disaster based on the major petroleum pipeline rupture, leak, and fire which tore through the middle of the City, killing three youths, in 1999. This incident, coupled with media coverage of the recent mega-disasters in the form of the Indian Ocean tsunami and Hurricane Katrina, reinforce community interest in disaster preparation.

This research relates to the U.S. Fire Administration's fourth operational objective, "To promote within communities a comprehensive, multi-hazard risk-reduction plan led by the fire service organization (National Fire Academy, 2004). Additionally, this research relates directly to the goal of the National Fire Academy's Leading Community Risk Reduction course, which is "To develop skills of the Executive Fire Officer to effectively implement a community risk-reduction initiative (Federal Emergency Management Agency [FEMA], 2004). The descriptive method will be used to carry out this research.

Literature Review

The phenomena known as a tsunami is a series of waves caused by underwater disturbances including earthquakes, volcanic eruptions, and landslides. The waves radiate from the area of disruption and can cross entire ocean basins at speeds of over 500 miles per hour (National Oceanic and Atmospheric Administration [NOAA], 2005). As the waves approach shore, they slow down and compress. In the best of conditions, the waves accompany an incoming tide and come gently ashore. In the worst cases, a wall of turbulent water, meters high, strikes the shore,

devastating the coastline. Following the waves can be a powerful, fast moving flood that can sweep away anything in its path. The water can recede, even to the point of exposing the seafloor, only to repeat the cycle with the arrival of the next tsunami wave (NOAA, 2005).

Tsunami waves were responsible for the deaths of over 229,000 people in the Indian Ocean region in December of 2004 (United Nations Office of the Special Envoy for Tsunami Recovery, 2006).

Tsunamis are divided into three general types depending on their travel time: near-field, mid-field, and far-field. Near-field tsunamis are locally occurring, often from landslides, and can arrive in minutes. Mid-field tsunamis include those with a source within 1000 kilometers, and may take between 30 minutes and 2 hours to arrive. Far-field, or teletsunamis, may occur on the far side of the ocean and take many hours to arrive (The National Tsunami Hazard Mitigation Program [NTHMP], 2006).

Likelihood of Tsunami

Off the coasts of southern British Columbia, Washington, Oregon, and Northern California lies the Cascadia subduction zone (CSZ). The CSZ is a long fault in the earth's crust where the oceanic Juan de Fuca plate is subducting underneath the North American plate (The Pacific Northwest Seismograph Network, 2002). The CSZ is similar to the Alaska-Aleutian fault that generated the 9.2 Richter magnitude (M) Alaska earthquake and tsunami, as well as to the Sunda fault that generated the 9.3 M Indian Ocean earthquake and tsunami in late 2004 (Lloyd, 2005; State Of California Seismic Safety Commission [SCSSC], 2005).

At least seven ruptures of the CSZ are observed in the geologic record, with intervals between 200 and 1000 years (SCSSC, 2005). The average interval is 500 years (Atwater et al., 2005). The most recent and well-documented rupture of the CSZ caused the 1700 Orphan tsunami. The Orphan tsunami was named in Japan, where most of the effects were documented,

because there was no apparent connection between the tsunami and the precipitating earthquake until almost 300 years later. Researchers, working along the coast of Washington State, discovered evidence that the land had dropped during the 1700 event, and then was washed over by a tsunami as evidenced by silt deposits. By comparing evidence of wave heights in Japan and Washington State, researchers concluded that the Orphan tsunami was sparked by a CSZ earthquake with an estimated magnitude of between 8.7 and 9.2 caused a rupture 1050 km long (Atwater et al.).

Atwater et al. (2005) suggested that the CSZ presents a 10% chance of producing a 9.0 M earthquake within the next 50 years. If, as the evidence suggests, the CSZ produces a major earthquake, a significant tsunami will likely accompany it (Whitmore, 1993).

In addition to the threat from CSZ centered events, several areas within the Puget Sound have been identified as having the potential to create tsunamis caused by landslides into, and underneath, the water (Gonzalez, 2002; Gonzalez et al., 2005). Experience from the 1964 Alaska earthquake demonstrated the potential for landslides to produce tsunamis (Gonzalez et al.). Landslides accounted for four-fifths (82) of the deaths due to tsunamis during that event (Powers, 2005). Also, a 6 m high wave experienced in Southern California in 1930 may have been caused by a submarine landslide subsequent to a 5.2 M earthquake (Darienzo et al., 2005).

Bellingham and some of its residents are included in the list of 489 Pacific Coast communities, and over 900,000 people, who live in areas vulnerable to a 50-foot tsunami (Eisner, 2005). The city was one of the Washington coastal communities selected for inundation mapping conducted by the State of Washington and NOAA (Walsh, Titov, Venturato, Mofjeld, & Gonzalez, 2004).

The findings of Atwater et al. (2005), Gonzalez et al. (2005), and Walsh, Titov, Venturato, Mofjeld, and Gonzalez (2004), reinforced awareness of the threat of tsunamis reaching Bellingham.

Extent of Inundation

The potential energy of a mid-field and far-field tsunami reaching Bellingham is expected to be dissipated by the buffering effect of underwater topography and the presence of the San Juan island archipelago. Whitmore (1993) predicted that tsunamis generated offshore would be less than one-sixth of the outer coast amplitude within the Puget Sound. Numerical modeling by Whitmore suggested maximum tsunami zero to peak wave amplitudes in Bellingham from an 8.8 M, 8.5 M, and 7.8 M CSZ earthquake as 0.59 m, 0.40 m, and 0.04 m respectively. The Whatcom County Natural Hazard Identification and Vulnerability Analysis identified a moderate to high vulnerability to tsunamis along waterfront areas (Whatcom County Division of Emergency Management [WCDEM], 2003).

Using a repeat of the 1700 9.1 M Cascadia earthquake as a scenario, the inundation map produced for Bellingham and the surrounding area predicts shallow inundation (0.5-2.0 m) along the shores of the City of Bellingham at the mean high water elevation (Walsh et al., 2004). A companion document (Venturato, Titov, Mofjeld, & Gonzalez, 2004) details that the initial 1.4 m wave will reach Bellingham approximately 2 hours after a CSZ earthquake, with the crest of the tsunami occurring between 2.5 and 3 hours post earthquake. A deep trough of approximately -3 m is projected at 4 hours, concentrated near Squalicum Harbor. Wave velocities along Bellingham's shoreline are expected to range between 0-1.5 meters per second (about 3 miles per hour), a speed at which it would be difficult to stand. As modeled, the entire event is expected to last approximately 7 hours from the time of the earthquake (Venturato et al.).

A significant stated limitation of the inundation map is that it does not include the influences of tidal stages and currents, both that may affect the power of a tsunami. The spring tide range in Bellingham Bay is approximately 8.5 ft, but can range as much as 13 ft (Walsh, Titov, Venturato, Mofjeld, & Gonzalez, 2004). The map narrative cautions that, “While the modeling can be a useful tool to guide evacuation planning, it is not of sufficient resolution to be useful for land-use planning” (Walsh et al.).

Based on research and analysis of the 2004 Indian Ocean tsunami, preliminary research by a team from the University of Rhode Island (URI) in cooperation with the Discovery television channel suggested that run-up from a CSZ generated tsunami could be up to three times higher than previously expected (Doughton, 2005; Roach, 2005). Instead of discovering expected evidence of underwater landslides, researchers found a 12-mile long break in the seafloor that was displaced up to 13 m during the earthquake (Roach). Given the similarities between the Sunda and Cascadia subduction zones, the team applied the findings to a computer model of a tsunami generation by the CSZ. The model showed run-up of up to 33 m in places along the Oregon and Washington coasts (Roach). Current inundation mapping is based on 16 m maximum run-up (Roach).

Tim Walsh, Geologic-Hazards manager for the Washington Department of Natural Resources, disputed the predictions as oversimplified (Doughton, 2005). Walsh (personal communication, May 2, 2006) stated the URI team’s model placed the CSZ in the wrong place, identified the CSZ as being 150 km longer than it is, and relied on an over simplified fault model. The model didn’t take into account the low fault angle (11-15 degrees) of the CSZ. “Even 100’ of slip, would only result in 12’-14’ of vertical displacement” Walsh said (personal communication, May 2, 2006). Walsh also stated that the URI researchers didn’t take into account the effect of local underwater topography in reducing tsunami energy (Roach, 2005).

Vasily Titov, a tsunami modeler with NOAA in Seattle, reinforced the URI team's predictions. Titov's model suggests run-up of up to 22 m along parts of the Washington coast, heights he was skeptical of until he personally viewed the effects of the Sumatran tsunami (Doughton, 2005). Walsh (personal communication, May 2, 2006) said that he is looking forward to a peer-reviewed article of the URI research.

The findings of Whitmore (1993), WCDEM (2003), Walsh, Titov, Venturato, Mofjeld, and Gonzalez (2004), and personal communication with Walsh (2006), developed this researcher's understanding of the likely extent of inundation of a tsunami reaching Bellingham.

Community Vulnerability

The Whatcom County Natural Hazard Identification and Mitigation report warns that a tsunami could kill many people and result in economic disaster. Possible effects listed include oil spills, fishing and pleasure fleet destruction, loss of ferry terminals and docks, disruption of rail lines, and undercutting of high banks (Whatcom County DEM, 2003). Building fires and hazardous materials releases are also frequently associated with tsunamis (SCSSC, 2005).

The destructive force of a tsunami is not only a function of its wave height, but also by how far it surges, or runs up, inland (Powers, 2005). Even a 5-foot tsunami creates more force and damage than a storm wave twice its size due to the force of the water behind it and its high speed. The Sumatran tsunami illustrated the risk to life, mainly from flooding and debris impact (SCSSC, 2005). A 5-foot tsunami wave can easily drown people (Powers). The 2004 tsunami inundation study of Bellingham concludes that flooding from a tsunami is expected mainly along the immediate shoreline, where evacuation to higher ground is easily done (Walsh, Titov, Venturato, Mofjeld, & Gonzalez, 2004).

Property damage due to tsunami is expected mainly from strong water currents and water-borne debris, and the exposure to the built environment is largely dependent on topography

(SCSSC, 2005). Whatcom County emergency management official Neil Clement stated, “Bellingham would see relatively minor damage because much of it is hilly or built high enough to be protected” (Johannes, 2005). However, in the Whatcom County Hazard Identification and Vulnerability Analysis, the vulnerability to tsunamis was classified as “Low overall, but Moderate to High for some areas” (WCDEM, 2003, p. 72).

Several sources identified the Port of Bellingham’s Squalicum Harbor as an area of concern. During a tsunami, boats can become projectiles and damage structures on-shore (SCSSC, 2005). Venturato, Titov, Mofjeld, and Gonzalez (2004) found that the 2004 inundation model does not indicate significant run-up into Squalicum Harbor. However, projected wave heights are approximately the same height as the protective seawall, making the harbor a potential hazard zone. Walsh (personal communication, May 2, 2006) cautioned that peak wave heights might float the docks over the top of their 10’ pilings. Conversely, Walsh et al. (2004) predicted that a 3 m trough could present a significant grounding hazard to boats in the harbor, especially if the trough occurred at low tide. Additionally, Walsh (personal communication, May 2, 2006) expressed concern for the life safety of boat owners who, with upwards of 2.5 hours notice, may want to get their boats out of the harbor into deep water before the tsunami arrives. “The resulting confusion may cause even more damage,” Walsh (personal communication, May 2, 2006) stated.

Damage due to a tsunami could be increased by earthquake related shaking and ground subsidence. During an earthquake, shaking can increase the water pressure of soil to the point the soil liquefies (the process of liquefaction) and settles (the process of subsidence) (The Pacific Northwest Seismograph Network, 2002). As the land drops, ocean water rushes into fill the void and/or a tsunami can more easily inundate the area (WCDEM, 2003). The geologic record indicates that parts of Coastal Washington dropped by as much as 10 m during earthquakes

(Collins, 2005a). Bellingham's waterfront, which consists largely of earth filling efforts over the last 100 years, is vulnerable to subsidence (WCDEM). In response to concerns expressed by professors at Western Washington University, the Port of Bellingham hired a geological consulting firm to report on the seismic-related hazards present at the New Whatcom redevelopment site on the central waterfront. Based on a review of the site's stratigraphy, the consultants suggested that 1-2 feet of subsidence is possible due to liquefaction within the fill and sand/deltaic soils could be expected during a major earthquake (GeoEngineers, 2006).

Research by Powers (2005) created a better understanding by this researcher of the physical effects of tsunamis. The work of Walsh, Titov, Venturato, Mofjeld, and Gonzalez (2004), and Venturato, Titov, Mofjeld, and Gonzalez (2004), built an appreciation of the vulnerability of Squalicum Harbor to the potential effects of tsunamis.

Mitigation Measures

Tsunami warning systems, evacuation planning, public education efforts, and engineering and zoning standards all play a role in reducing risk to life and property from the effects of tsunamis. There are two general types of warnings of an impending tsunami, direct observation or experience of natural phenomena; and warning systems, such as sirens, that are linked to the Tsunami Warning Centers (Darienzo et al., 2005). Depending on the source, the warning time before a tsunami can arrive can be measured in minutes in the case of a near-field tsunami, to hours for a far-field tsunami (Darienzo et al.). Crawford, Mofjeld, and Weaver (2001) approximated warning times for the different types of tsunamis affecting the Puget Sound as shown in Table 1. The stated goals for providing warnings of an impending tsunami are 30 minutes for a far-field event, 10-15 minutes for a mid-field event, and 5 minutes for a local event (Collins, 2005b).

Table 1

Warning Times for Puget Sound Region Tsunamis

Type	Source	Warning Time
Local (<i>near-field</i>)	Local earthquakes and landslides	1 minute
Regional (<i>near-field</i>)	Cascadia subduction zone	0.5 – 3 hours
Trans-Pacific (<i>far-field</i>)	Alaska and Asia	4 hours +

Note. From “Summary of Puget Sound Tsunami/Landslide Workshop, January 23 and 24, 2001,” by G. Crawford, H. Mofjeld, and C. Weaver, 2001, Pacific Marine Environmental Laboratory website. Adapted with permission of the author.

Tibballs (2005) suggested that the most accurate warning of a tsunami is the sign of the ocean suddenly receding. This sign may provide people with up to 5 minutes of warning of an impending tsunami. Darienzo et al. (2005) found that interpretation of natural phenomena can be subjective, and may be processed incorrectly even by educated people.

Originally developed in reaction to the tsunami that devastated Hawaii in 1946, NOAA’s Tsunami Warning Center is responsible for monitoring tsunami propagation and providing early warning to vulnerable communities (SCSSC, 2005). The West Coast / Alaska Tsunami Warning Center serves the west coast including Washington State (SCSSC). Given that a far-field tsunami can reach the coast of the western U.S. in as little as 15 minutes, warnings are issued quickly. Any earthquake registering 7.0 M or greater near the west coast generates a tsunami warning. After the initial warning is transmitted, scientists evaluate additional information (such as data from ocean buoys) to determine whether or not to maintain or cancel the warning (Oppenheimer et al., 2005).

The warning system relies on 1950’s technology and the system does not take advantage of modern dissemination systems such as text messaging (SCSSC, 2005). Connect and Protect, an initiative of a technology consortium in Portland, Oregon, alerts paid subscribers directly of

official warnings as well as significant ocean-based seismic events potentially affecting the west coast (Verton, 2005).

A reliable warning system is worthless if the target population is aware of the warning and fails to respond appropriately (Daud, 2005). Escaping from the effects of a tsunami is dependent on personal action. Quickly recognizing the signs of a tsunami, or hearing the warning, and moving out of the inundation zone is paramount (SCSSC, 2005). To that end, a program of continuous and effective public education is a key tool in creating a tsunami ready community (Darienzo et al., 2005). Elements of the program may include school presentations, brochures, media releases, and signs. The signs should be posted in the hazard area and indicate the evacuation route to safety (Whatcom County DEM & Summit GIS, 2004).

A 2001 survey of residents along Washington State's southwestern coast indicated that awareness of tsunami hazards was high, but preparedness was low. Johnson et al. (2005) found that few residents had taken steps to personally prepare for a tsunami, instead relying on other elements in the community. A multi-pronged approach of public education, social policy, training, and empowerment strategies were suggested to convert intentions into preparedness behaviors (Johnson et al.).

Evacuation can save lives of many if properly executed. However a poorly coordinated evacuation can actually put people at risk (SCSSC, 2005). Tsunami inundation maps serve as the basis for effective evacuation planning. Numerical simulations, animations, and geographic information system (GIS) files are used to produce these scientifically grounded maps (Gonzalez et al., 2005).

Collins (2005b) noted the extraordinary vulnerability of emergency responders to the effects of tsunamis. Many earthquake prone jurisdictions direct their fire department crews to perform a post-earthquake "windshield survey" of their response districts to identify damage and major

problems. If these surveys, or a major emergency, take the responders into a tsunami inundation zone, the responders are at risk of being caught in a tsunami. Many firefighters on the Japanese Island of Okusire died in this manner in 1993 when they were overwhelmed by a tsunami while in the process of fighting an earthquake-caused fire along a waterfront area (Collins).

Tsunamis present an interesting challenge to land use planners and development regulators. Not only is the probability of tsunamis difficult to assess because of their infrequent occurrence, but also when they do occur, their effects can be catastrophic (Eisner, 2005). Adding to this dynamic is the premium economic value attached to coastal development.

The NTHMP created a guide for planners and regulators to mitigate the effects of tsunamis through land use and development policy, site planning, and building design (NTHMP, 2001). The guide is based on the premise that “Losses from tsunamis can most effectively be mitigated by avoiding or minimizing the exposure of people and property through land use planning” (NTHMP, p. 15). The measures detailed included avoiding development in run-up areas altogether, configuring sites to minimize losses, constructing buildings to minimize damage, and taking care in placement of critical facilities in inundation areas. The guide also suggested methods of protecting existing development through redevelopment, retrofit, and land reuse planning (NTHMP).

Whatcom County’s Natural Hazard Mitigation Plan recommends that new critical facilities planned for a tsunami hazard zone must be elevated above the hazard, armored in place, or, ideally, built elsewhere (WCDEM & Summit GIS, 2004). Reinforcing this recommendation, Walsh (personal communication, May 2, 2006) suggested that the vulnerable areas of the proposed New Whatcom redevelopment project along Bellingham’s central waterfront should be elevated approximately 5’ to reduce the threat of tsunami. GeoEngineers (2006) suggested

mitigation strategies for New Whatcom to include installing a 2-3 foot tsunami bulkhead, strengthening buildings, and tying down floating objects such as roads and utilities.

Building codes do not take into account the unique forces likely generated by tsunamis (NTHMP, 2001; International Code Council, 2006). Once water enters the structure, and then water levels quickly draw down outside, walls are at risk to collapse outwards (SCSSC, 2005). FEMA's Coastal Construction Manual (FEMA, 2000) addresses the loads created by tsunamis, but concludes that tsunami loads are too great to feasibly design structures to withstand these loads. The City and County of Honolulu adopted special requirements for floods and tsunamis in flood hazard districts. Some of these provisions vary with recommendations in the Coastal Construction Manual (SCSSC, 2005).

Information on likely warning times of an impending tsunami by Darienzo et al. (2005), and Crawford, Mofjeld, and Weaver (2001), as well as Tibball's (2005) identification of the signs of a tsunami, served to reinforce conclusions by Walsh et al. (2004), that timely evacuation does not present a significant challenge along Bellingham's waterfront. The findings of Johnson et al. (2005) pointed out that public education efforts do not necessarily produce the behaviors desired.

Local Tsunami Plans

In 2004, Whatcom County's Division of Emergency Management contracted with a local GIS firm to produce a multi-jurisdictional natural hazards mitigation plan for the county. The purpose of the plan was "To reduce the loss of life and property due to natural disasters and to enable mitigation measures to be implemented during immediate recovery from a disaster" (WCDEM & Summit GIS, 2004 p. 1). The plan refers to hazard mitigation planning as a collaborative process, in which hazards are identified, vulnerabilities assessed, and consensus is reached on how to minimize the effects of the hazards (WCDEM & Summit GIS). Eight general-purpose governments, as well as the Port of Bellingham, participated in the planning efforts.

Importantly, completion of the plan contributed to Washington State's eligibility for funds allocated by FEMA's Hazard Mitigation Grant Program.

Tsunamis were one of the six hazards highlighted in the plan. Earthquakes, floods, geologic hazards, volcanoes, and wildland fires were the remaining hazards (Whatcom County DEM & Summit GIS, 2004). The 2004 map detailing the tsunami hazard in Bellingham (Walsh et al., 2004) served as the basis for the plan's vulnerability assessment. As a mitigation strategy, the plan referred to NOAA's Developing Tsunami Resistant Communities program (Bernard, 2005) as a model. The program includes public education efforts, evacuation planning, warning signs, alert systems, and land use planning to reduce the danger posed by tsunamis (WCDEM & Summit GIS).

Specific hazards and mitigation strategies were identified for each jurisdiction. The section on the City of Bellingham classified less than 100 structures, and less than 5% of the total land area, to be at risk from the effects of a tsunami (WCDEM & Summit GIS, 2004). The only critical facility listed as being at risk to tsunami was the U.S. Coast Guard station at Squalicum Harbor. However, later in the document, the city's wastewater treatment plant, because of its location near sea level along the waterfront, was identified as needing additional study to assess its risk and to identify mitigation options (WCDEM & Summit GIS). Although predominantly located within the City of Bellingham, the Port of Bellingham's hazard and mitigation strategies were listed separately. No port facilities, including Squalicum Harbor, were listed as being at risk from the effects of tsunamis (WCDEM & Summit GIS, 2004).

Review of the Whatcom County Natural Hazards Mitigation Plan caused this researcher to question the accuracy and completeness of local planning to address the threat of tsunamis.

Procedures

This descriptive research relied heavily on published materials. The literature search began in early February, 2006, and continued throughout the project. The search started with the Online Card Catalog of the Learning Resource Center at the National Emergency Training Center. This source proved invaluable in providing the bulk of books and journal articles accessed. Additional materials were identified through the Internet using the Google, and Google Scholar search engines. The Digital Bibliography of the Geology and Mineral Resources of Washington proved valuable as it included the Tsunami Library of the National Tsunami Hazard Mitigation Program. Keywords used in searching these sources included “tsunami, earthquake, subduction zone, fault, Cascadia, and inundation.” Personal contacts with Whatcom County’s Division of Emergency Management, the Port of Bellingham, and the Washington Division of Geology and Earth Resources provided background information and consultation. The City of Bellingham Public Works Department’s GIS Division provided a topographical map and assessed property value of Bellingham’s waterfront to assist with development of the vulnerability analysis.

In an attempt to better understand the potential tsunami threat to the community, a risk assessment methodology presented in the Leading Community Risk Reduction course and manual (Federal Emergency Management Agency, 2004) was used. The process consisted of rating the probability of tsunami occurrence; rating community vulnerability based on five factors: danger/destruction/personal harm, economic, environmental, social, and political; and lastly, multiplying the probability rating by the vulnerability rating to arrive at an overall risk rating. To assist in assigning the vulnerability rating, a field survey was conducted to identify all of the structures and estimated people located in the inundation zone as detailed in the tsunami inundation map of Bellingham (Walsh et al., 2004).

The primary limitations of this research were the relative infrequency of major CSZ earthquake events, and the elapsed time since the last such event in 1700. Both factors limited the ability to accurately forecast how a CSZ generated tsunami would affect the inhabitants and built environment of present day Bellingham, Washington.

Results

The first research question sought to establish the probability of a tsunami reaching Bellingham. Bellingham's proximity to the CSZ, local geological features, and the existence of a federally sponsored inundation map of the area speak to the potential of tsunamis reaching Bellingham. SCSSC (2005) reported seven past ruptures of the CSZ in the geologic record. Whitmore (1993) suggested that, if the CSZ produces a major earthquake, a tsunami would likely accompany it. Atwater et al. (2005) found evidence of 1700 CSZ generated tsunami in this region. Lloyd (2005) drew parallels between the CSZ and other known tsunami generating faults in Alaska and Sumatra. Gonzalez (2002), and Gonzalez et al. (2005) identified several areas within the Puget Sound that are thought to have the potential to cause tsunamis due to landslides into, or underneath, the water. Based on priorities of at-risk coastal communities set between geologists and state emergency management officials, Bellingham was selected as the subject of an inundation map completed by Walsh, Titov, Venturato, Mofjeld, and Gonzalez (2004). Atwater et al. (2005) found that the CSZ produces a major earthquake on an average of once every 500 years, and suggested that there is a 10% chance of a tsunami-generating 9.0 M CSZ earthquake within the next 50 years.

Using the scale to assess the probability of an event occurring (unlikely, possible, likely) contained in the Leading Community Risk Reduction Student Manual (FEMA, 2004), there is possibility of a tsunami reaching Bellingham. However, the hazard presented to the community

as a whole is minimal as the effects of a tsunami are expected to be limited to the areas along the immediate shoreline.

The second research question intended to identify the likely extent of tsunami inundation into Bellingham. In general, the potential energy of a mid-field or far-field tsunami reaching is expected to be dissipated by the buffering effect of underwater topography and the presence of the San Juan Islands. Whitmore (1993) predicted that, for tsunamis generated offshore, the amplitude within the Puget Sound would be one-sixth of what is experienced on the outer coastline. For Bellingham specifically, the inundation map produced by Walsh, Titov, Venturato, Mofjeld, and Gonzalez (2004) provides a graphic illustration of the likely inundation area. The map depicted shallow inundation (0.5-2.0 m) along the central and northern waterfront of Bellingham at mean high water elevation. The map did not show inundation inland of the main rail line operated by Burlington Northern Santa Fe, and did not indicate any inundation of the Southside waterfront area (Walsh et al.).

The third research question asked, “What elements, if any, of Bellingham are vulnerable to the threat of tsunamis?” To address this question, five areas of community exposure were considered: danger/destruction/personal harm, economic, environmental, social, and political. The inundation map for Bellingham (Walsh et al., 2004) served as the guide to define areas at risk.

Danger/destruction/personal harm can be thought of as the vulnerability to life and property. Given the limited extent and shallow depth of inundation expected in Bellingham, and the ease of evacuation to higher ground, risk to life from a tsunami is expected to be low. Notable exceptions include boat owners who may be caught in a wave while attempting to move their craft out to deeper waters (Walsh, personal communication, May 2, 2006), and emergency responders caught along the waterfront conducting operations after an earthquake (Collins,

2005b). Similarly, although there are upwards of 100 buildings and improvements located within the inundation zone with a combined assessed value of \$247,785,350 (Bellingham GIS, Personal communication, June 6, 2006), the shallow level of inundation is not expected to cause major damage to property along the waterfront. The area of greatest area of concern for property damage is Squallicum Harbor. In addition to the 1285 slips for pleasure boats and 132 slips for commercial (fishing) vessels, the harbor is also home to the main facility of the Bellingham Coast Guard Station, and a fireboat. Depending on tide levels upon the arrival of a tsunami wave, overtopping of the protective seawall and dock support system may take place, and/or grounding of boats. Either scenario has the potential to cause extensive damage to the harbor's infrastructure and vessels. Table 2 summarizes, by International Building Code use and occupancy classification (International Code Council, 2006), the buildings and estimated numbers of people vulnerable to inundation.

Table 2

Number of people and buildings subject to inundation, organized by use

Use and Occupancy Type	# of People	# of Buildings
Assembly	200	5
Business	165	10
Factory	336	19
High Hazard	2	2
Mercantile	90	7
Residential	30	1
Storage	100	19
Utility / Miscellaneous	51	10
Total	974	73

Note. Number of people is an estimate of daytime population.

Although there are a limited number of injuries expected, more extensive damage may occur, yielding the danger/destruction/personal harm factor a rating of 2 (moderate) for areas within the inundation zone.

The economic factor considers incident control costs and the loss costs to arrive at an economic measure of the event (FEMA, 2004). Incident control costs are expected to be minimal as the forces generated by a tsunami defy emergency control efforts. The major financial impact will likely be realized during the recovery phase due to property loss and business disruption. A study completed in consideration of a new downtown marina (BST Associates, 2006), estimated that the Port of Bellingham's existing marinas (including the smaller, 600 slip Blaine facility) generate 204 direct jobs within the county. Each of these jobs generates an additional 0.37 jobs to account for 279 total jobs within the county (BST Associates). Including multiplier effects, BST estimated that the marinas generate approximately \$8.1 million in total income, \$48.5 million in total output, and \$800,000 in in-state and local taxes each year. Squalicum Harbor has been at full capacity since 2005, and a 600-slip demand is projected by 2015 (City of Bellingham, 2006).

Given that the economic effects of a tsunami reaching Bellingham would likely be temporary and are not expected to exceed personal or community fiscal limitations, the economic risk factor earns a rating of 2 (temporary) for areas within the inundation zone.

Significant environmental impacts of a tsunami reaching Bellingham are not expected. Elements included in this assessment include the potential compromise of food and water supplies, wilderness values, loss of rare or endangered plants and wildlife, and either permanent destruction or environmental recovery greater than 1 year. A rating of 1 (low) is assessed for the potential of environmental impacts within the inundation zone of Bellingham.

Social aspects involve safety and security, historical values, recreation values, and social services. Potential effects in this realm include displacement of the occupants of the 100 live-aboard boats in Squalicum Harbor, and temporary loss of recreational uses due to boat and park damage. Overall, a tsunami reaching Bellingham may cause minor social upheaval, affecting some cultural values. A rating of 2 (moderate) is assigned for the impact on social aspects.

The last factor involves the level of governmental response and planning involved in managing a tsunami. Because of the short duration predicted for an event, and because many other communities are far more vulnerable to much greater devastation from tsunamis than Bellingham, emergency response efforts can be expected to take place at the local level. During the recovery phase, however, state and Federal governments may be involved as partners with local government. Given that local government is expected to play the central role in managing the affects of a tsunami, a rating of 1 (local) is assigned to the political element.

Based on a combination of the impact ratings from the different elements, the area of Bellingham within the mapped inundation zone has a low (5-8) vulnerability to the effects of tsunamis. Table 3 summarizes these findings.

Table 3

Tsunami Hazard Vulnerability Assessment

Factor	Rating	Impact
Danger/destruction/personal harm	2	Moderate
Economic	2	Temporary
Environmental	1	Low
Social	2	Moderate
Political planning level	1	Local
Total vulnerability	8	Low

The fourth research question sought to identify the measures available to mitigate the effects of a tsunami. Resting under the broad banner of the NTHMP's Tsunami Resistant Community initiative, a broad array of mitigation tools are available. The three major tools are building and land use regulations, evacuation planning, and the use of warning systems. Examples of regulatory measures include constructing buildings to minimize damage, configuring sites to minimize loss, taking care in the placement of critical facilities, and avoiding development in inundation areas altogether (NTHMP, 2001). Major components of effective evacuation planning include scientifically establishing the risk through inundation mapping, distributing brochures detailing evacuation routes out of the inundation area, posting evacuation route signs, and conducting drills to reinforce evacuation behaviors. Lastly, warning systems such as sirens, weather alert radios, and telephone based notification systems that are linked to the tsunami warning system can be used to alert the public about the potential of a tsunami.

There are two plans in existence to mitigate the effects of a tsunami reaching Bellingham. The first is the inundation map (Walsh et al., 2004) and companion document (Venturato et al., 2004). The map provided a graphic illustration of the likely extent of inundation into Bellingham, and the companion document detailed the specific effects expected from a tsunami reaching Bellingham. Taken together, these two documents serve as a scientific basis for evacuation planning but, because of sea level fluctuations caused by tides, are not accurate for land-use planning (Walsh et al.). The other plan of note is the "Whatcom County Natural Hazards Mitigation Plan." This plan identified the six most significant natural hazards facing the county, and then focused in on the hazards, vulnerabilities, mitigation strategies, and action plans for specific governmental entities within the county. Agency representatives from the various entities assisted in development of jurisdiction specific content. The plan identifies that Bellingham is at risk to the effects of tsunamis, especially areas within the Port of Bellingham

(WCDEM & Summit GIS, 2004). In addition the Coast Guard station, the city's waste water treatment plant (located near the shore on the Southside of the city) was identified as being potentially at risk from tsunamis, and needing additional study to quantify the risk and identify alternatives for mitigation (WCDEM & Summit GIS). The question of how these plans should be improved is one of personal opinion and will be addressed in the next section.

Discussion

Overall, the research results reinforced information discussed in the Literature Review. In regards to the probability of a tsunami reaching Bellingham, the result that tsunamis are a hazard to Bellingham relied on the scientific agreement (Atwater et al., 2005; SCSSC, 2005) about the potential for a CSZ earthquake; that the earthquake could cause a tsunami (Gonzalez, 2002; Gonzalez et al., 2005; Whitmore, 1993); and the possibility of a tsunami reaching Bellingham (Walsh et al., 2004).

Disagreement, however, was noted between sources identified in the Literature Review regarding the likely extent of inundation into Bellingham. The results relied on what appeared to be the best, peer-reviewed, science reflected in the inundation map for Bellingham (Walsh et al., 2004) that modeled shallow inundation along the immediate shoreline in Bellingham. Predictions made by the URI researchers (Doughton, 2005; Roach, 2005), and Titov (Doughton), were discounted as they appeared to be based on incorrect assumptions about CSZ fault behavior and were not published in a peer reviewed format.

The results concurred with the opinion of Clement (Johannes, 2005), and the findings of Walsh et al. (2004), that the effects of a tsunami reaching Bellingham would be limited, with Squalicum Harbor presenting the greatest area of risk. Research illustrated the significant economic impact the harbor has in the community in terms of jobs, tax revenue, and total economic output. Results suggested that areas of Bellingham within the inundation zone had low

vulnerability to the effects of tsunamis, whereas Whatcom County's Natural Hazard Identification and Vulnerability Analysis noted that the vulnerability to tsunami was moderate to high in some areas (Whatcom County DEM, 2003). The report, however, did not specify which areas of the county were considered to be in the hazard zone.

Results relating to measures available to mitigate the effects of a tsunami relied on information gleaned in the literature review. Specifically, program elements of NTHMP's Tsunami Resistant Community initiative served as accepted best practices to lessen the effects of tsunamis. Plans for the re-development of the New Whatcom site presented an opportunity to assess local application of land use and development mitigation measures detailed in the Literature Review (NTHMP, 2001; WCDEM & Summit GIS, 2004). Recommendations from GeoEngineers (2006) to install a bulkhead, strengthen buildings, and to tie down floating objects appear to be consistent with best practices.

Descriptions of the plans, which address local tsunami mitigation issues, were consistent between the Literature Review and Results sections. As to the question of how these plans should be improved, this researcher noted apparent gaps in the two plans that should be reconciled. The first issue involves the inundation map (Walsh et al., 2004) and companion document (Venturato et al., 2004). These documents illustrate and describe the potential for inundation along Bellingham's central and northern waterfront, but ignore the Southside. The Southside waterfront is of the same general elevation above sea level, and much of it shares the same westerly exposure with other waterfront areas in the city. Critical facilities are located along the Southside's waterfront included the city's wastewater treatment plant, the Alaska Ferry Terminal, and a satellite Coast Guard dock berthing two cutters. A significant number of manufacturing businesses were also present. Clearly identifying the relative vulnerability of the Southside would be a valuable improvement to the inundation map and companion document.

Improvements in both process and content are in order for the county's Natural Hazard Mitigation Plan. Best practices for hazard mitigation planning, as detailed in the National Fire Academy's Leading Community Risk Reduction course (National Fire Academy, 2004), promote the use of a collaborative process to reach consensus on approaches to hazard mitigation. Although the plan claims to rely on this collaborative approach, that was not the experience of this researcher during his personal involvement in the development of the plan. Instead, group interaction was minimized, and the involvement of key stakeholders was limited to verifying lists of critical facilities and independently developing jurisdiction specific mitigation strategies. Results of this disconnected process, and failure to rely on the best available science, are visible in the plan. For instance, the plan does not identify that port facilities, including Squallicum Harbor, are at risk from tsunamis. This plan should be improved by engaging a broad range of stakeholders (not simply governments) to use a collaborative process in order to identify hazards and agree on mitigation strategies.

This research created awareness that, as a stand-alone event, tsunamis present a low risk to the City of Bellingham. As a coastal community who is well aware of the catastrophic effects of the Indian Ocean tsunami and Hurricane Katrina, this is a critical understanding. The research further highlighted, however, the vulnerability of our community to the effects of a CSZ generated earthquake measuring 9.0 M or greater. In the event of this occurrence, a tsunami might be the least of concerns. The organizational implication of this awareness is the need to make disaster preparedness planning a critical priority for city government.

Recommendations

In response to the results of this research, the Bellingham Fire Department should take the following steps:

- Facilitate a dialog within city government to clarify the goals of, results expected, and responsibility for disaster preparedness efforts. Evaluate the effectiveness of the contractual relationship with Whatcom County for emergency management functions.
- Restructure the natural hazard mitigation planning process to include a collaboration of key stakeholders from throughout the community. Using the model presented in the National Fire Academy's Leading Community Risk Reduction, expand the process to include all hazards facing the community.
- Seek clarification from the inundation map authors as to the vulnerability of shoreline areas along the Southside of Bellingham to tsunamis.
- Follow up with Washington State's Department of Natural Resources to obtain tsunami evacuation maps, brochures, and signs for distribution into the inundation area.
- Delete directions to travel into waterfront areas from post-earthquake survey maps used by fire companies.

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